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The use of light weight deflectometer for in situ evaluation of sand degree of compaction

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Sand density

Abstract The light weight deflectometer (LWD), also known as the light falling weight deflectometer, light drop weight tester, and dynamic plate load test, is a hand portable device that was developed in Germany to measure the soil in situ LWD dynamic modulus. Typically, this modulus is used to evaluate the subsoil degree of compaction. Thus it is suitable for compaction quality control of soil-surfaced roads, embankments and replacement fill. As a dynamic test, the device is suited, in particular, for coarse and mixed grained soils with a maximum grain size of 63 mm. The response of poorly graded calcareous and siliceous sands is the focus of this research. First, the index soil properties of the tested soils including grain size distribution; maximum and minimum void ratios and specific gravity were obtained. Petrographic analyses of the tested sands were also performed to determine their mineralogical composition. A 1-m^3 chamber was built for performing the LWD testing in the laboratory. The study was performed for relative densities of 20%, 40%, 60% and 80% to represent the behavior of very loose, loose, medium dense and dense sands. The effect of the existence of a rigid boundary beneath the tested soil on test results was also investigated to determine the zone of influence of the light weight deflectometer.

1. Introduction

The light weight deflectometer (LWD) is a hand portable falling weight device that first appeared in 1981 at Magdeburg, Germany and developed as in situ testing device by the Federal Highway Research Institute, and HMP Company in Germany [1]. The LWD has gained acceptance and popularity in several countries such as the United States, as there is a growing interest in the use of LWD as in situ spot-testing device for quality control and quality assurance of earthwork compaction [2]. The device was first introduced to Egypt in 2008 for testing both natural subgrade and compacted fill commercially in field work.

The light weight deflectometer is also known by other names including; light falling weight deflectometer, light drop weight tester, and dynamic plate load test. Different types of LWD are commonly available around the world, but are very similar in principle. This research is performed using the LWD No. (1.06.01) produced by HMP Company, which is provided in the German specification [2] to check the suitability of this

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device for predicting the degree of compaction of the two specified sands.

2. Description of light weight deflectometer

The LWD device consists of the following elements which are illustrated in Fig. 1.

1. A top fix and release mechanism which holds the falling weight at a constant height. This mechanism is released to allow the falling weight to freely drop and transmit the load pulse through the plate resting on the material to be tested.
2. A guide rod that allows the falling weight to drop freely at a set distance of about 720 mm. The guide rod and falling weight together weigh approximately 15 kg.
3. A falling weight grip which provides a grip for the operator to raise the falling weight to the top fix and release mechanism.
4. A falling weight which typically varies between 10 and 20 kg. This weight is capable of being raised to the bottom of the grip predetermined height. The weight is guided by a low resistance rod when dropped to impart a controlled force on the loading plate.
5. A lock pin which has two positions (locked and unlocked) to release the falling weight for use.
6. A damping system which provides a controlled transient pulse length to the impact force, typically in the range of 16 to 30 ms. The spring element is typically a series of rubber cones/buffers, or cylindrical pad system.
7. An anti-tipping fixture that prevents the guide rod and falling weight from tipping when these parts are placed and standing freely on the load center ball/loading plate. A load center ball serves as a connector between the anti-tipping fixture and the loading plate. It also allows for disassembly which reduces the size of the instrument for transport.
8. A cup with sensor that connects to an electronic device and is installed in the middle of the plate. It records the movements of the plate even while the test is being carried out.
9. Carry grips to assist the operator with carrying the loading plate.

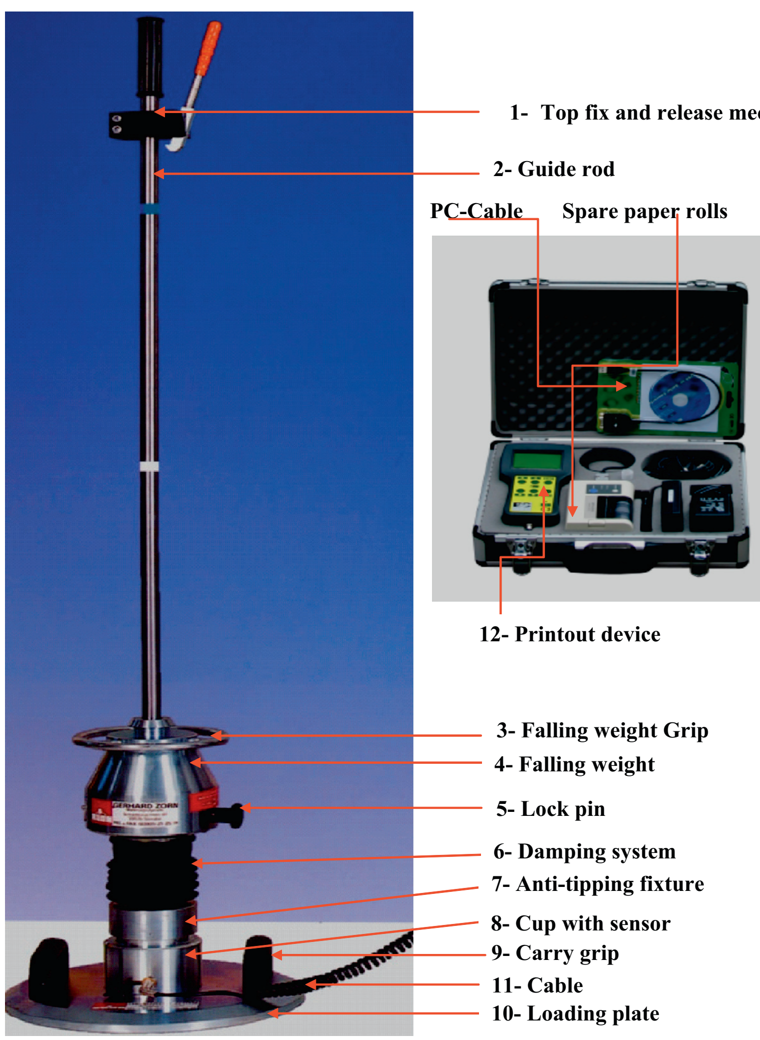


Fig. 1 Components of light weight deflectometer [3].

10. A loading plate which provides an approximate uniform distribution of the impulse load on the surface. The diameter typically varies from 100 to 300 mm and the loading plate weighs about 5 kg.
11. A cable is used to connect the loading plate sensor to the data processing and storage systems. Each measurement can immediately be allocated to the relevant position using GPS. All data can be displayed on the printout electronic device without problems.
12. A printout electronic device which is suitable for self-supervision and documentation of measurements. A data capture system is required with software to display the impact test results and store them. Additionally, the relevant site and position details can be logged along with the captured data [4].

3. LWD test procedures

The testing area should be leveled so that the load plate can be placed on an even surface. Loose particles on the surface should be removed and the load plate must be in contact with the material being tested. The diameter of the test area should be at least 1.5 times larger than the plate diameter [5].

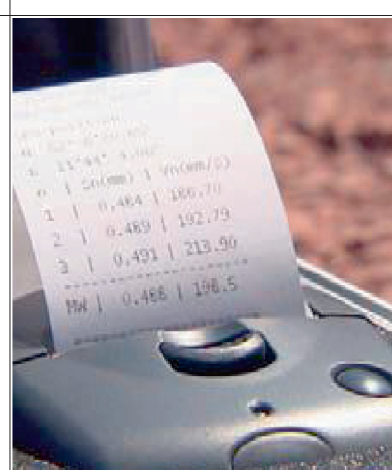
After the test area is prepared and the load plate is positioned on the surface, the loading device is centered on the loading plate and the device for measuring the deflection amplitude at the center of the load plate is made ready for testing, as shown in Fig. 2a.

The loading device is connected with the readout unit through a cable, as shown in Fig. 2b. The guide rod is placed with the falling weight on top of the loading plate. The lock pin

(a) Putting the load plate on level surface

(b) Connecting the mechanical part and electronic unit with a cable

(c) Preparing the device for testing



(d) Results Printouts

Fig. 2 The light weight deflectometer (LWD) test procedures [1].

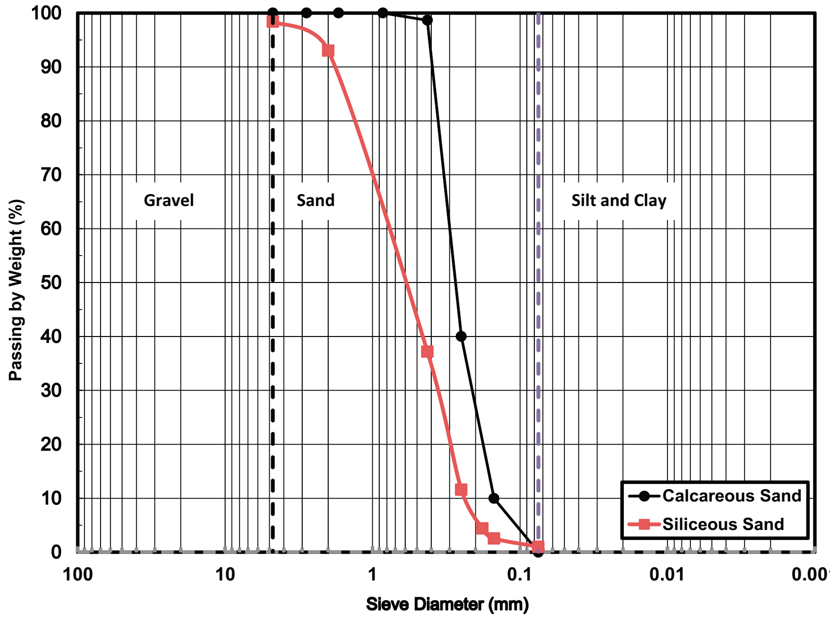


Fig. 3 Grain size distribution curves of calcareous and siliceous sand.

Table 1 Summary of index properties of tested sands.

Sand	G_S	D_{10} (mm)	D_{90} (mm)	C_u	e_{min}	e_{max}	$\gamma_{dry\ max}$ (kN/m^3)
Calcareous	2.74	0.18	0.4	1.67	0.48	0.67	17.9*
Siliceous	2.63	0.22	0.9	3.2	0.406	0.644	18.9*

* Based on modified proctor test.

is pulled from the drop weight and turned 90° to release the weight.

Care must be taken to ensure that the drop weight falls exactly from the specified height, as shown in Fig. 2c.

The test should be repeated when the impact loading causes lateral displacement of the loading plate e.g., when the test is performed on excessively sloping ground.

Three initial drops should be made in order to get good contact between the plate and the soil then three reloading drops are made. The results are stored on a memory card and a printout obtained onsite as shown in Fig. 2d. Each test takes approximately two minutes which is a relatively short period.

The LWD modulus is evaluated using the static plate load test [6].

$$E_{LWD} = 1.5\ R\ \sigma/s \tag{1}$$

where, E_{LWD} = LWD deformation modulus, R = radius of the loaded plate, σ = stress under the loaded plate, s = mean settlement of the loaded plate.

The above equation does not consider the speed related factors and inertial forces in the test evaluation. The stress under the plate is generally constant and equal to 0.1 MN/m^2 and for a plate diameter of 30 cm. Thus, the above equation reduces to E_{LWD} (MN/m^2) = 22.5/s (mm), which is used to calculate the LWD modulus based on the measured settlement which is automatically performed by the LWD software.

4. Properties of the tested sands

4.1. Engineering properties

All testing was conducted on calcareous and siliceous sand samples to investigate the effect of sand mineralogy on the results. The calcareous sand has a fairly uniform gradation with grain sizes mostly ranging between 0.07 and 0.5 mm. It has a very low fine content, less than 0.1% passing sieve number 200. According to Unified Soil Classification System, the calcareous sand is poorly graded (SP). The siliceous sand used in this study is also classified as poorly graded (SP) according to the Unified Soil Classification System with the grain sizes varying between 4 and 0.07 mm. The percentage of fines passing sieve number 200 is less than 2.6%. The grain size distributions of both the calcareous and siliceous sands are shown in Fig. 3.

Several soil index properties, including specific gravity, effective grain size D_{10}, maximum and minimum void ratios and maximum unit weight using the modified Proctor test were obtained for both sands. Tests were performed in accordance with the current Egyptian Code of Practice or relevant ASTM standard. A summary of the results is given in Table 1.

4.2. Mineralogy of the tested sands

Soil mineralogy greatly influences its behavior. X-ray diffraction (XRD) is a powerful technique that provides detailed data

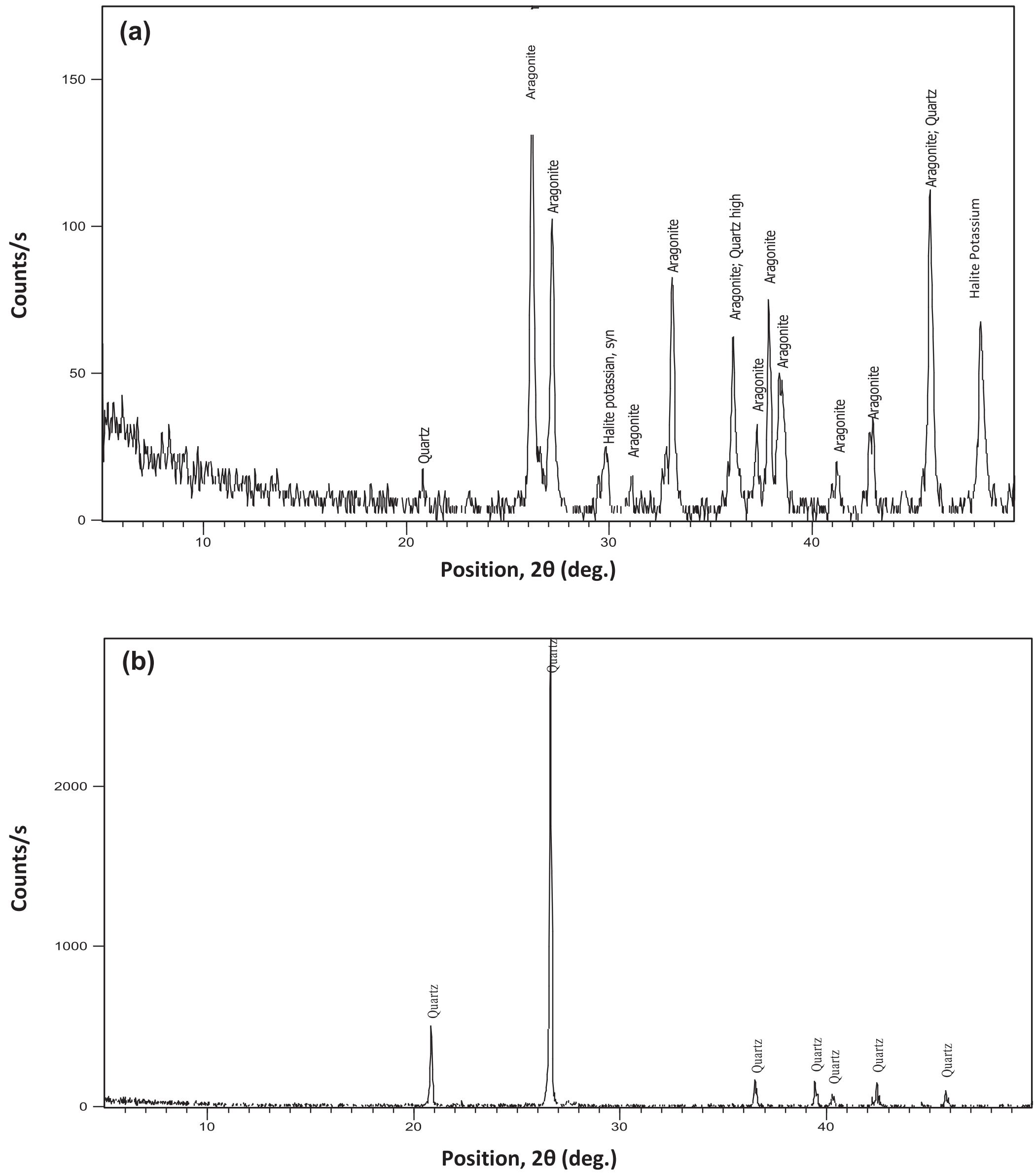


Fig. 4 Mineral compositions of (a) calcareous and (b) siliceous sand.

about the atomic structure of the crystalline substances to identify the constituent minerals. Both calcareous and siliceous sands were examined using XRD as presented in Fig. 4a and b for both sands, respectively. The X-ray diffraction analysis shows that the calcareous sand is composed of 97% percentage of Aragonite that represents calcium carbonate ($CaCO_3$), and a low percentage of Quartz (0.16%). While the siliceous sand specimen is composed of 96% percentage of Quartz.

4.3. Petrographical study

A petrographical study was carried out on specimens of the tested sands by taking microscopic images of specimens from the calcareous and siliceous sands as shown in Fig. 5a and b. Fig. 5a shows the calcareous sand to be composed of calcite as a major constituent with very small amounts of Quartz. The specimen also contained fossil shells and corals that include cavities and voids on the surface and inside the particles. The microscopic picture of the siliceous sand specimen is shown in Fig. 5b which indicates that the sample is composed mainly of quartz with considerable amounts of halite potassium. The image shows that the siliceous sand particles to be angular.

5. Experimental testing program

Four target relative densities 20%, 40%, 60%, and 80%, were selected to represent the very loose, loose, medium dense and dense states for both sands, respectively, to study the effect of sand density on the LWD modulus. This research also examined the depth of influence on the LWD modulus by varying the thickness of the compacted sand layer.

A box 1000 mm long × 1000 mm wide × 1000 mm deep was specially built to carry out the planned testing program. The

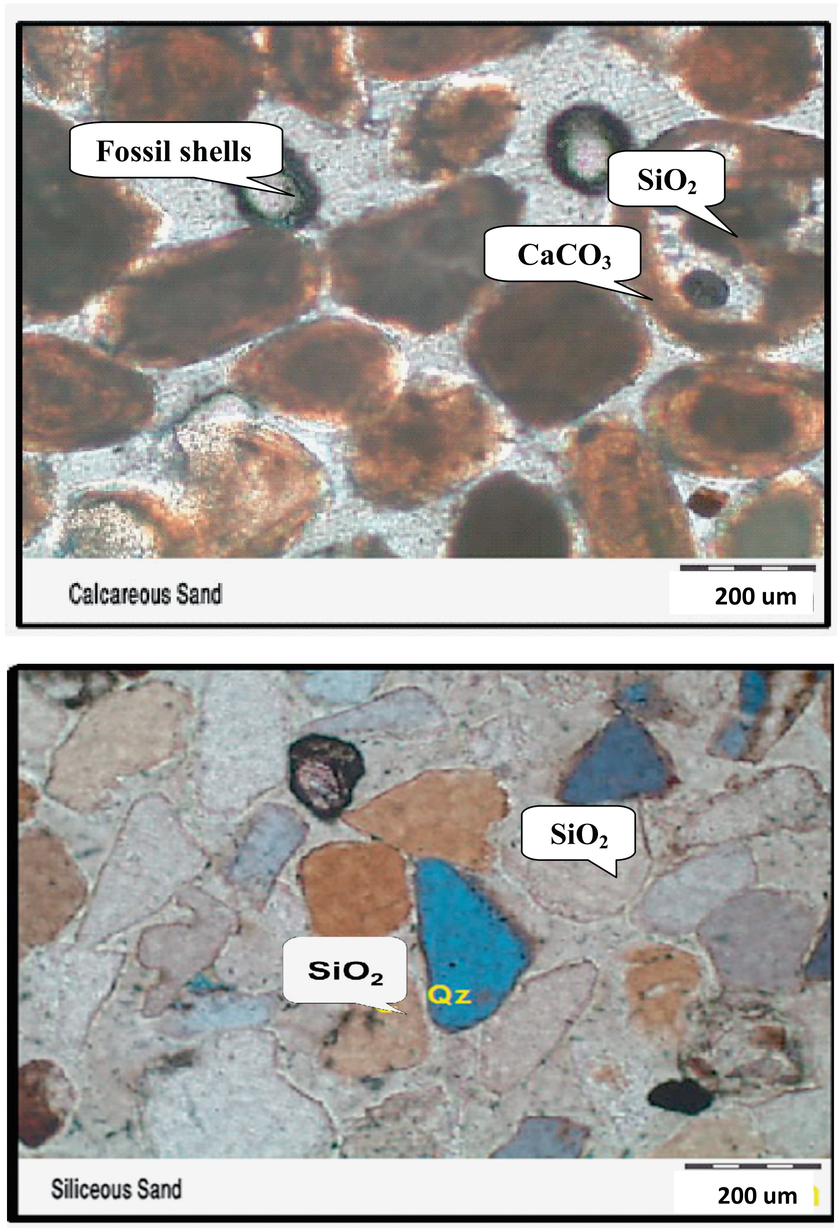


Fig. 5 Microscopic photographs of (a) calcareous and (b) siliceous sand.

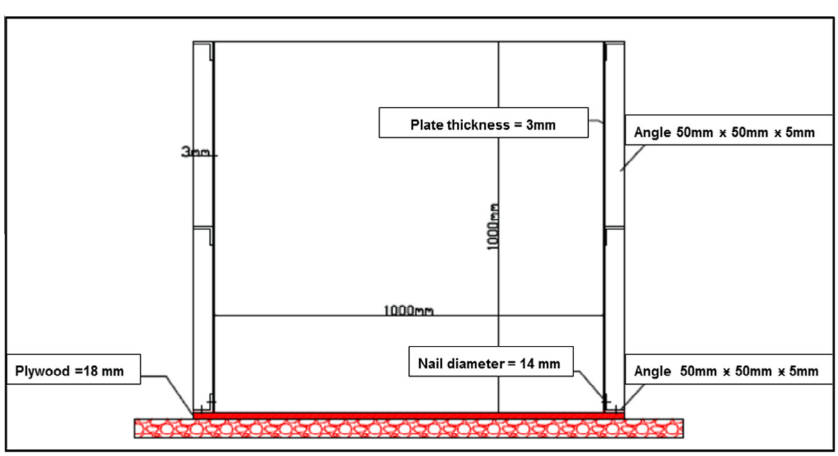


Fig. 6 Cross section in the testing chamber.

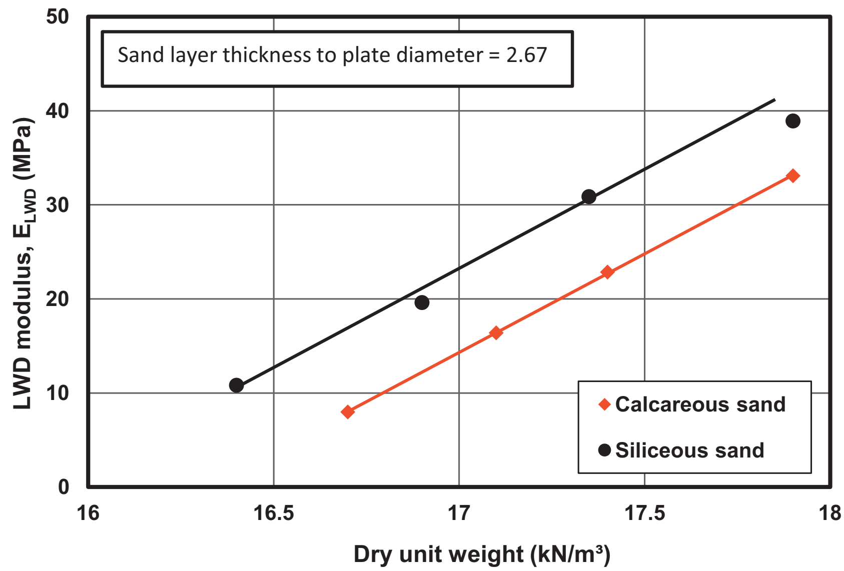


Fig. 7 Effect of sand unit weight on LWD modulus (E_{LWD}).

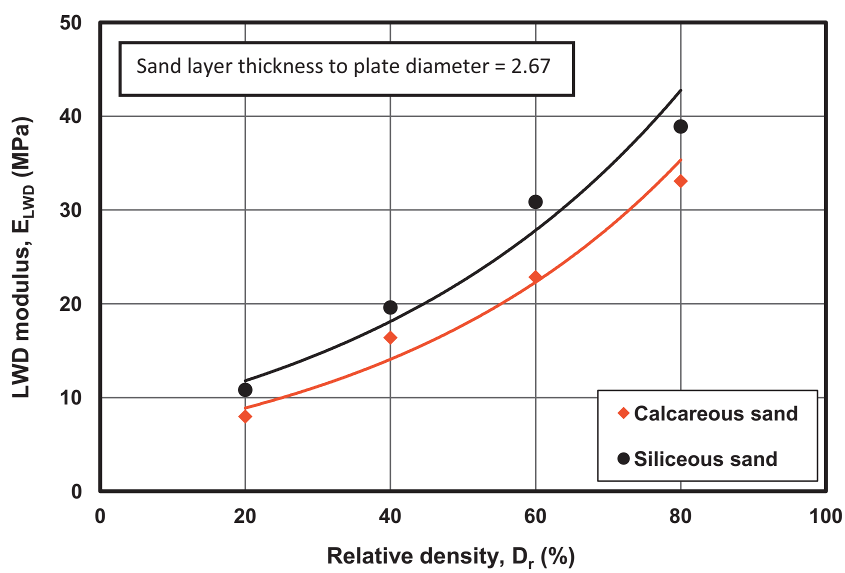


Fig. 8 Effect of sand relative density on LWD modulus (E_{LWD}).

chamber consists of four plates of mild steel with thickness of 3 mm. One of the chamber sides is moveable to facilitate sand removal after the completion of each test. The chamber base is made from 18 mm thick plywood resting directly on the concrete floor. A section in the testing chamber is shown in Fig. 6. Soil was placed in the chamber by tamping using a 5 kg hammer in layers of thickness varying between 10 and 20 cm to different relative densities. The sand density was calculated by dividing the weight of the sand placed into the chamber by the volume. Sand placement ensured the uniformity of the relative density within the testing chamber by monitoring the sand unit weight for each placed layer. The effect on the test results that may be caused by the chamber sides is small and may be neglected [7].

6. Experimental results

6.1. Effect of soil density on LWD modulus

Both calcareous and siliceous sands were prepared to the target relative densities with layer thicknesses of 80-cm (sand layer thickness to LWD diameter of 2.67), then the LWD test was performed. Fig. 7 shows the relationship between the LWD modulus and the sand dry density for both tested sands. The results indicate that measured LWD modulus increases by an average rate of approximately 21 MPa for an increase in unit weight of 1 kN/m^3 for both calcareous and siliceous sands. For the same unit weight, the measured LWD modulus

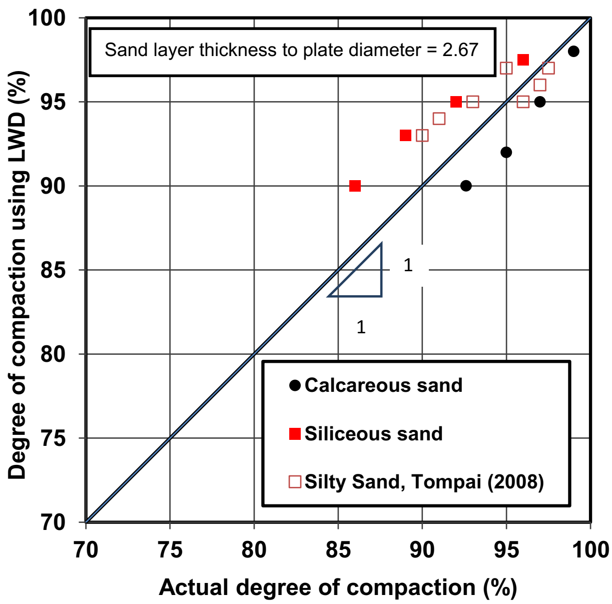


Fig. 9 Comparison between the actual degree of compaction and DIN degree of compaction from LWD.

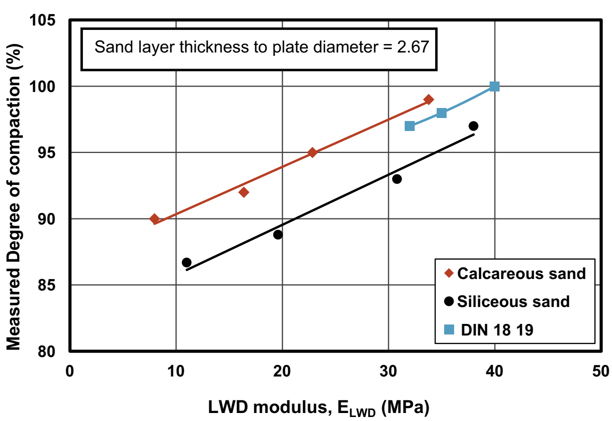


Fig. 10 Relationship between LWD modulus (E_{LWD}) and the degree of compaction.

for siliceous sand is higher by approximately 10 MPa compared to calcareous sand. These findings agree with the observations of Abu-Farsakh et al. (2004) [8] that show that the LWD modulus (E_{LFWD}) increases with dry unit weight for poorly graded crushed lime stone, poorly graded sand, and recycled asphalt pavement.

The relationships between the sand LWD modulus and the corresponding relative densities are plotted in Fig. 8 for calcareous and siliceous sands. As expected, the LWD modulus increases with the increase in sand relative density. For the same relative density, the measured LWD modulus is higher for siliceous sand compared to calcareous sand. This may be attributed to the angularity of the siliceous sand particles compared to the rounded shape of the calcareous sand particles in addition to the voids and fossils that exist in the calcareous sand as shown by the petrographic study. Furthermore, the higher crushability of calcareous sands compared to siliceous sands could explain the experimental results.

6.2. The relation between LWD modulus and degree of compaction

One of the main uses of the light weight deflectometer is the quality control of fill placed in the field. The degree of compaction is defined as the ratio of the in situ density to the maximum laboratory dry density. It may be evaluated from the LWD indirectly by empirical correlations between the LWD modulus and degree of compaction. One of the most used correlations for evaluating the degree of compaction from LWD results is the German additional technical specification and guidelines for earth works in road construction [9]. The actual measured degrees of compaction were compared to values deduced using the DIN correlation, as shown in Fig. 9 for both calcareous and siliceous sands. The results show that the accuracy of the DIN relationship is better for degrees of compaction of 95% or higher. Lower accuracy is noted for degrees of compaction less than 95%. This may be explained knowing that the DIN relationship is provided for degrees of compaction higher than 95%. The graphs also show the results from Tompai [10] that were performed on silty fine sand samples confirm the findings of the current study.

Fig. 10 shows the relationship between the measured degrees of compaction versus the LWD modulus for the tested sands as well as the DIN relationship. Similar to the relationship between the sand relative density and LWD modulus, Fig. 10 shows that for the same degree of compaction, the LWD modulus of siliceous sand is higher than that of calcareous sand. The curve LWD modulus versus degree of compaction for calcareous sand and siliceous sands bound the DIN relationship which may be considered as an "average" for both sand types.

6.3. Zone of influence of the LWD

The zone of influence of the LWD is investigated by performing the LWD test on calcareous and siliceous sands placed in layers with varying thicknesses (10, 20, 40, 60, and 80 cm) resting on a rigid boundary (concrete floor). Fig. 11 shows the relation between the LWD modulus and the thickness of the sand layer normalized to the LWD plate diameter of 300 mm for calcareous sand compacted to relative densities of 20%, 40%, 60% and 80%. The results show that the LWD modulus increases as the thicknesses of the sand layer decrease as the measured modulus is affected by the rigid layer. Thus, the LWD reading reflects the stiffness of both the tested soil and the rigid boundary. The influence of the rigid base boundary on the LWD modulus diminishes with increasing the thickness of the sand layer. For soil layer thickness to plate diameter ratios of 1.5 to 2, the effect of the rigid layer is considered negligible. Tests performed using siliceous sands show similar findings as presented in Fig. 12. Tompai [10] and Nazzal [11] found the zone of influence of the LWD to vary between 1 and 2 times the plate diameter in agreement with the findings of this study.

7. Summary and conclusions

The light weight deflectometer is a rapid test method for compaction quality of soils and unbound base courses in earthwork and road construction. The light weight deflectometer

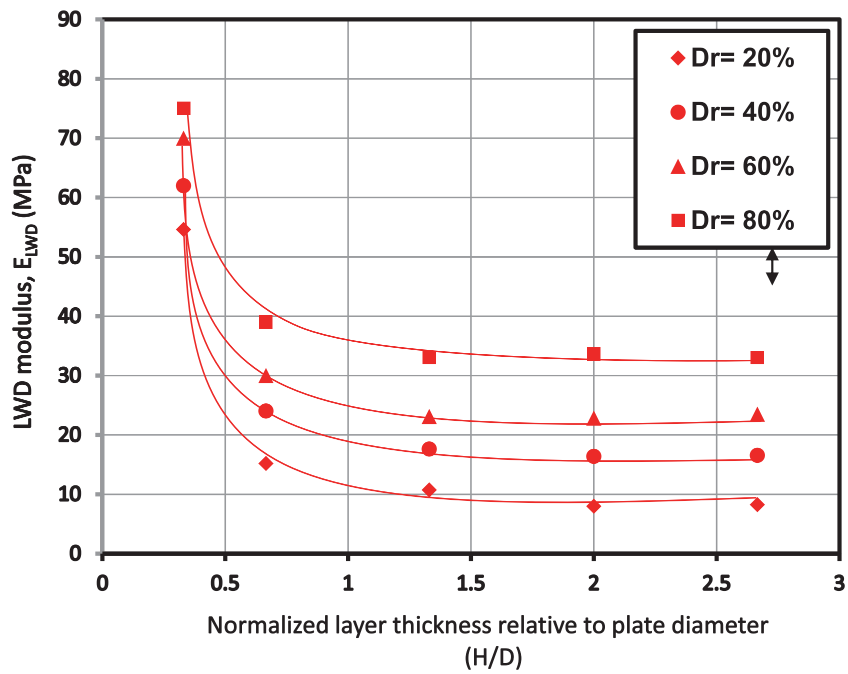


Fig. 11 Effect of the existence of a rigid boundary on LWD modulus for calcareous sand.

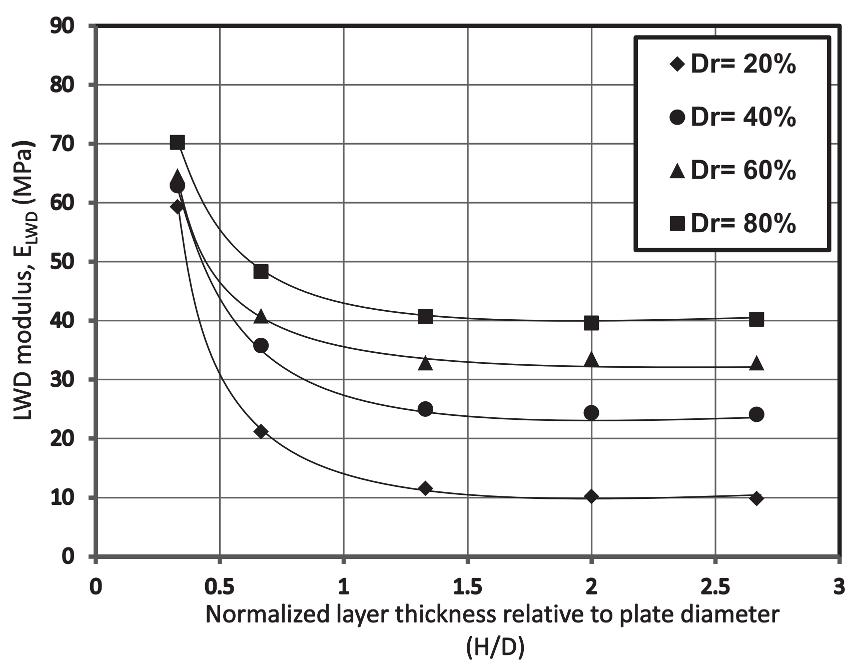


Fig. 12 Effect of the existence of a rigid boundary on LWD modulus for siliceous sand.

measures the soil dynamic LWD modulus which is empirically correlated to the soil degree of compaction. Based on laboratory chamber testing, the following conclusions are deduced.

1. For the same relative density, the LWD deflectometer modulus for siliceous sand is higher than the LWD modulus for calcareous sand.
2. The relationship between the LWD modulus and degree of compaction given in DIN 18 196 [8] is evaluated for estimating the degree of compaction for calcareous and siliceous sands. The measured degrees of compaction for calcareous and siliceous sands bound the DIN relationship may be considered as an “average” for both mineralogies.

3. The DIN 18 134 relationship provides higher accuracy for estimating degrees of compaction higher than 95% which may be explained by the fact that the DIN relationship is originally given for degrees of compaction higher than 95%.
4. The zone of influence of the light weight deflectometer is found to be 1.5 to 2 times the diameter of the LWD plate.

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